Proceedings of ICRC 2001: 2235 © Copernicus Gesellschaft 2001

ICRC 2001

ECCO: Th/U/Pu/Cm dating of galactic cosmic ray nuclei

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Abstract. The ECCO instrument is one of two instruments which comprise the HNX mission. The principal goal of ECCO (the Extremely-heavy Cosmic-ray Composition Observer) is to measure the age of galactic cosmic ray nuclei using the actinides (Th, U, Pu, Cm) as clocks. As a bonus, ECCO will search with unprecedented sensitivity for long-lived elements in the superheavy island of stability. ECCO is an enormous array (23 m^2) of BP-1 glass track-etch detectors, and is based on the successful flight heritage of the Trek detector which was deployed externally on Mir. We present a description of the instrument, estimates of expected performance, and recent calibrations which demonstrate that the actinides can be resolved from each other with good charge resolution.

1 Measuring GCR age using Th/U/Pu/Cm dating

Dating of ancient terrestrial and solar-system material using the long-lived actinide isotopes ^{232}Th, ^{235}U and ^{238}U as clocks has a long and distinguished history. Recently, elemental Th/U dating has been used for the first time to measure the age of an object *outside* the solar system, the ultra-metal poor star CS31082-001 (Cayrel *et al.*, 2001). We plan to measure the age of the galactic cosmic rays (GCRs) using essentially the same technique, using the Extremely-heavy Cosmic-ray Composition Observer (ECCO), a giant array of BP-1 glass track-etch detectors in space. ECCO, along with ENTICE (Israel *et al.*, 2001), are the two instruments onboard the Heavy Nuclei Explorer (HNX) (Binns *et al.*, 2001), which has been selected by NASA under the Small-class Explorers (SMEX) program for Phase A study. Here we describe the ECCO instrument, discuss its expected performance, and present a recent calibration in which we demonstrate experimentally that individual GCR actinides can be resolved.

ECCO is based on the successful flight heritage of the Trek detector, which was deployed on the outside of the Russian space station *Mir*. Using Trek, in an analysis in which we used only 12 out of 32 possible measurements for each GCR ion, we measured the abundances of the elements with $Z > 70$ in the galactic cosmic rays with a charge resolution of $0.45e$, which was a $\sim$ 3-fold improvement in resolution over the previous state of the art (Westphal *et al.*, 1998). Recently, we have improved this resolution to $\sim 0.35e$ by analyzing the entire detector (Weaver, 2001). Both measurements confirm the results reported earlier by the HEAO (Binns *et al.*, 1989) and Ariel (Fowler *et al.*, 1987) collaborations that Pb is severely depleted in GCRs compared to the what would be expected if GCRs originate in solar-like material with preferential acceleration biased by first ionization potential (FIP). Such a severe depletion of Pb may be expected, however, if GCRs either originate in gas and dust grains in the interstellar medium (Meyer, Drury and Ellison, 1997), or in material dramatically enhanced in r-process material (Binns *et al.*, 1989). A measurement of GCR age can decide between the two scenarios, since GCR nuclei would be expected to be ancient (several Gy) in the first, and very young ($\sim$ 10 My) in the second.

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2 The ECCO instrument

The principal goal of ECCO is to measure the abundances of the individual actinides (Th, U, Pu and Cm), both with respect to each other and with respect to the Pt-group elements. Because of the scarcity of actinides in galactic cosmic rays — as in Nature in general — a very large instrument with a long exposure time is required to achieve sufficient statistics to accurately establish age. ECCO will be an array of 250 independent 900 cm^2 detector modules, deployed in two pallets, and will orbit the Earth for at least three years. The total instrument area is 23 m^2, and its mass is 2115 kg. Each module will consist of a monolithic block of BP-1, 2.5 cm thick, sandwiched between two 1.5 mm-thick BP-1 hodoscopes and two 1.0 mm-thick BP-1 preliminary charge identification modules (PCIMs) (Fig. 1). The modules are symmetric with respect to the detector plane, so can analyze particles arriving from either direction.

During the exposure in space, the detectors will record the tracks of relativistic heavy galactic cosmic rays which traverse them. After recovery, the detectors will be returned to the laboratory where they will be disassembled. The first step in the analysis will be to etch the BP-1 hodoscopes in our most senstive etchant, fluoboric acid, removing 190μm of material from each surface. The latent tracks of GCR ions will etch faster than the bulk of the glass, producing large conical etchpits at each surface penetrated by the GCRs. GCRs of sufficiently large charge ($Z > 73$ for highly relativistic ions) will produce tracks which etch so rapidly that penetrating holes are formed in the hodoscope layers. These holes are detected trivially by an ammonia gas-transfer technique (O'Sullivan *et al.*, 1996). After the candidate particles are located and their trajectories determined using the hodoscope data, the tracks of the cosmic rays are cored out of the monolithic detectors using an automated CNC mill. The cylindrical cores are exposed at two angles to a highly relativistic heavy ion beam (e.g., the 10.6 GeV/amu Au beam at the AGS) — we explain the function of these exposures below. The cores are then diced into thin (1.5mm) wafers, and the wafers are individually ground, polished and etched. The etchpits of the GCR ion and of the calibration beam are precisely measured using automated scanning microscopes (see below). The calibration exposures now serve three purposes: first, they can be used to calibrate the detector to compensate for small differences in sensitivity; second, the calibration beams at two angles can be used to very accurately measure the amount of material removed by etching in a later stage of the analysis; and third, the crossed beams are used to locate detector planes to much better than 10 μm with respect to each other.

An essential requirement of this technique is that the latent track is not modified by the dicing or surface preparation of the detectors, since these operations are done *after* the latent track is formed. (This is in contrast with the Trek detectors, which consisted of stacks of thin glass detectors which were ground and polished *before* deployment in space.) In other words, latent track formation and surface preparation must

Table 1. Half-lives and expected r-process yields of the long-lived actinides

Element	Half-life ($\times 10^6$ yr)	r-process yield ([Th]≡1.0) (Pfeiffer *et al.*, 1997)
^{232}Th	14 100	1.0
^{235}U	704	0.94
^{236}U	23	0.68
^{238}U	4 470	1.26
^{244}Pu	81	0.59
^{247}Cm	15.6	1.06

commute. We have demonstrated that surface preparation of detectors after latent track formation has no effect on signal magnitude or dispersion (Westphal and Weaver, 2001).

After etching, the etch-pits of the GCR and surrounding calibration etch pits will be accurately measured using four automated microscopes. Such an automated microscope has been used for many years at Berkeley to rapidly and accurately scan glass track-etch detectors. In this case, both scanning and handling of wafers will be completely automated, requiring operator attention no more than once per day. Wafer identification and tracking will be handled by bar-coding each wafer; the barcode will be read automatically by the scanning system. The bar-coding technique is being very successfully used by the ATLAS collaboration for tracking hundreds of thousands of parts. The wafers will be delivered to the microscopic scanning systems using commercially available wafer-handling robotic systems. This robotic wafer handling technology has strong heritage in the semiconductor industry, and is reliable and readily available.

The geometry of the etchpits is converted to a signal, and by measuring the signal as a function of flight distance through the detector, and comparing to the known, calibrated response of the detector, the charge and energy of the particle are reconstructed. The entire data analysis, including derivation of source abundances, will require less than two years to accomplish.

3 Expected statistics and resolution

ECCO has sufficient collecting power that if the GCR source is young, Cm will be detected with high confidence even if the r-process yield of Cm is extremely and unexpectedly small (Fig. 2). Most recent r-process calculations predict much larger Cm yields, with Cm/Th $\sim$1 (Pfeiffer, 1999). With its active area, ECCO will collect a minimum of 110 actinides, the expected statistics if the GCRs originate purely in the ancient ISM, and $\sim$285 actinides if GCRs originate purely in freshly synthesized material. The actual GCR source may be a mixture of old and young material. Based only on the U/Th ratio, ECCO will be sensitive to an admixture of fresh r-process material with local galactic material at the 6% level (Table 2), which will test the hypothesis of OB association origin of GCRs (Higdon, 1998). On the other extreme, for a source that is principally fresh, with abundances as pre-

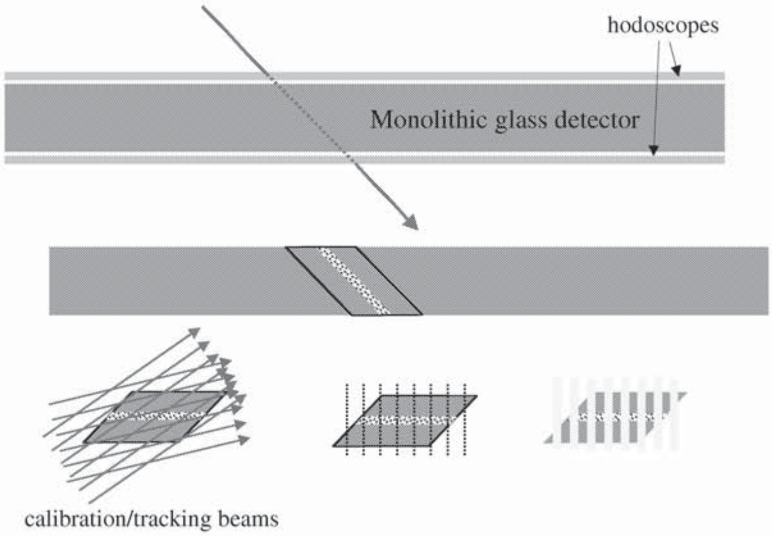

Fig. 1. Schematic of layout, coring, calibration and dicing of an ECCO detector.

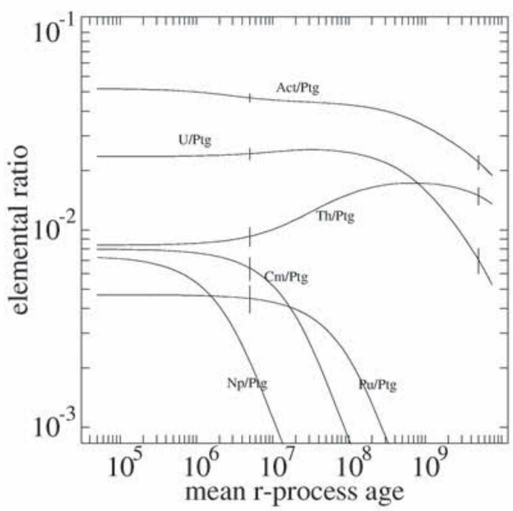

Fig. 2. Predicted abundances of the individual actinides with respect to the Pt-group, as a function of mean GCR age, with r-process yields of Kratz *et al.*(Pfeiffer *et al.*, 1997) and uniform synthesis. Expected error bars are shown..

dicted by Kratz, et al (1997), ECCO is sensitive at the 1σ level to an admixture of $\sim 13\%$ of local galactic material.

For the analysis of Trek, we studied over 20 sources of dispersion in charge measurement (Weaver *et al.*, 1997). Five sources were significant. For ECCO, only the first remains significant. The use of calibration beams at two exposure angles allows both a precise measurement of the thickness of material removed by etching (G), and simultaneously a precise measurement of the local response of the detector to the calibration beam. This is a well-established technique (Weaver *et al.*, 1997). On-orbit track fading is essentially eliminated by maintaining a detector temperature well below 25°C. Charge state switching and nuclear fragmentation are easily detected and accounted for because of the very fine (750μm) sampling of the particle track and the superb charge resolution of BP-1 in a single measurement. We can trade statistics for resolution. Our high-statistics data set will include all events with the minimum flight distance, 25mm, and will have charge resolution $\sigma_Z < 0.35e$. The high-resolution data set will include all events with a larger flight distance, 35mm, but will have charge resolution $\sigma_Z < 0.25e$. We point out that the long-lived actinides are all separated by two charge units, so even in the high- statistics data set the charge resolution will be a factor of ~ 2 better than required to resolve them.

4 Demonstration of Th-U separation

Using the 1 GeV/amu U beam at GSI, we have demonstrated experimentally that ECCO detectors can separate Th from U with good resolution. In Fig. 3 we show the measured signal as a function of depth for 1 GeV/amu ^{238}U, and a Th fragment, probably near $A = 232$ in mass. The signal due to Th is shifted so that the first measurement coincides with the curve due to uranium. The Th signal diverges rapidly from the uranium signal with increasing depth. The curve labelled "^{232}Th" is not a fit to the Th data, but is a prediction of the ^{232}Th signal as a function of depth, based only on the observed uranium signal and our improved range-energy calculations (Weaver, 2001).

5 Bonus Science

As a bonus, the ECCO instrument will carry out the most sensitive search to date for long-lived superheavy elements,

Ratio	ISM origin	90% ISM + 10% fresh	freshly synthesized (Pfeiffer *et al.*, 1997)
Act/Pt-group ($\times 0.01$)	1.85 ± 0.18	2.13 ± 0.19	4.63 ± 0.23
Th/Pt-group ($\times 0.01$)	1.28 ± 0.15	1.23 ± 0.19	0.83 ± 0.12
U/Th	0.45 ± 0.09	0.62 ± 0.12	2.88 ± 0.47
Pu/Pt-group ($\times 0.01$)	< 2.3	4.0 ± 2.3	59 ± 14
Cm/Pt-group ($\times 0.01$)	< 2.3	7.2 ± 3.2	106 ± 21

Table 2. Expected values of actinide ratios, assuming a) a pure ISM origin of GCRs; b) a source consisting of 90% ISM and 10% freshly synthesized material and c) freshly synthesized material. r-process yields were calculated by the ETSFI-Q model of K.-L. Kratz and colleagues(Pfeiffer *et al.*, 1997).

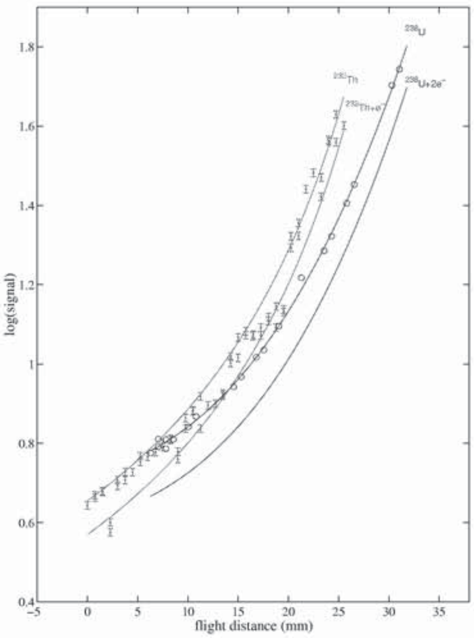

Fig. 3. Experimental demonstration of separation of Th and U at 1 GeV/amu.

which are expected to lie in the island of stability near $^{288}110$ and $^{290}110$ (Notation is ^{A}Z) (Möller and Nix, 1994). These isotopes lie on the neutron-rich side of the island of stability, and are difficult or perhaps impossible to synthesize in fusion-based laboratory synthesis. But if superheavy elements are synthesized in the r-process, neutron-rich isotopes are inevitably produced; some might have sufficiently long half-lives to survive to be detected. Indeed, it is most appropriate to conduct a search for such isotopes in the youngest sample of matter to which we have access, the GCRs.

Finally, motivated by calculations of nuclear stability, which indicate that strange quark matter may be more stable than ordinary matter (Medina-Tanco and Horvath, 1996), there have been several searches in recent years (e.g., Isaac *et al.* (1998)) for nuggets of strange quark matter in the GCRs. HNX will carry out the most sensitive search to date for such particles in a mass range between 10^8 amu and 10^{13} amu that is inaccessible to ground-based searches. The signature of such a particle would be an enormous signal corresponding to an ionization rate far beyond that of even superheavy elements.

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